Observation of circular mechanical modes in micron-sized graphite resonators coupled to superconducting 3D cavities and coplanar waveguides

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Electromechanical systems coupled to superconducting microwave cavities have received extensive interest in recent years due to their promising prospects as test beds for quantum ground state cooling of macroscopic objects like silicon nitride membranes. Apart from silicon nitride membranes, resonators made from exfoliated graphite graphene are interesting objects to cool down due to its layer-dependent mechanical properties and electrical properties. Such properties allow the resonator to have high mechanical Q-factor and strong parametric coupling with the cavity. In our work, we narrate our efforts in coupling macroscopic layered material resonators to 1) superconducting microwave coplanar waveguides and 2) rectangular waveguide cavities. We resolved circular plate mode frequencies for several suspended graphite drums with diameters ranging from 14 μm to 102 μm. We also observed frequency doubling of a fundamental mode at strong probe tone driving, implying quadratic coupling. With modest improvements in the measurement setup, we can cool down large layered-material device resonator via dynamical backaction. These platforms can be extended to other 2-D layered materials including monolayer graphene and transition metal dichalcogenides.

Inelastic Cooper Pair Tunneling: Generation of Non-Classical Microwave Radiation

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Usually, Cooper-pair tunneling through a Josepshon junction is elastic: the dc voltage across the junction has to be zero to allow tunneling through the junction. But tunneling can occur also at non-zero bias if the energy of a tunneling Cooper pair can be dissipated somewhere[1]. This dissipation can be provided by an open transmission line taking away the Cooper-pair energy in the form of photons[2]. Without special care, tunneling events are independent, leading to Poissonian or bunched statistics of the emitted photons. However, by designing particular high-impedance electromagnetic environments, the photon statistics can become non-classical[3]. We have implemented such a high-impedance circuit, connected to a small SQUID, which allows us to produce anti-bunched photons. By modulating the flux through the SQUID we can emit anti-bunched photons on demand at rates up to $> 100\,\mathrm{MHz}$

[1]T. Holst *et al.*, Phys. Rev. Lett. **75**, 3455 (1994)
[2]M. Hofheinz *et al.*, Phys. Rev. Lett. **106**, 217005 (2011)
[3]J. Leppäkangas *et al.*, Phys. Rev. Lett. 115, 027004 (2015)

Electron-phonon interaction and superconductivity in $SrAu_2Si_2$

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Based on first–principles pseudopotential plane wave method within the generalized gradient approximation, we have studied structural and electronic properties of $SrAu_2Si_2$. The calculated electronic properties for $SrAu_2Si_2$ show three–dimensional rather than two–dimensional characteristics. The electronic structures and phonon dispersion relations of this material have been analyzed. By integrating the Eliashberg spectral function α^2F(ω), the average electron-phonon coupling parameter is determined to be $\lambda = 0.42$ for $SrAu_2Si_2$. Using a reasonable value of $\mu^* = 0.12$ for the effective Coulomb repulsion parameter, the superconducting critical temperature T_c for $SrAu_2Si_2$ is found to be 0.57 K.

Stationary Nano-SQUID: Theoretical Investigation and Feasibility Analysis

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The standard operation of a dc SQUID leads to oscillatory electric fields that emit electromagnetic radiation. We estimate the effect that this radiation could have on the measured sample. A stationary SQUID could be advantageous if the oscillation contribution to back action on the measured sample has to be avoided. We study a superconducting loop that encloses a magnetic flux, connected to a superconducting and to a normal electrode, when a fixed electric current between the electrodes flows across the loop. The considered circuit does not contain Josephson junctions. We find that in a very broad range of parameters the current flow converges to a stationary regime, i.e. the densities of normal current and of supercurrent become functions of position only, independent of time. The potential difference between the electrodes depends on the magnetic flux, so that measuring this voltage would provide information on the enclosed flux. The influence of thermal noise was estimated. The sizes of the voltage and of the power dissipation could be appropriate for the design of a practical fluxmeter. We found narrow ranges of flux at which the voltage varies sharply with the flux.

Magnetic disorder in superconductors: Enhancement by mesoscopic fluctuations

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We study the density of states (DOS) and the transition temperature T_c in a dirty superconducting film with rare classical magnetic impurities of an arbitrary strength described by the Poissonian statistics. We take into account that the potential disorder is a source for mesoscopic fluctuations of the local DOS, and, consequently, for the effective strength of magnetic impurities. We find that these mesoscopic fluctuations result in a non-zero DOS for all energies in the region of the phase diagram where without this effect the DOS is zero within the standard mean-field theory. This mechanism can be more efficient in filling the mean-field superconducting gap than rare fluctuations of the potential disorder (instantons). Depending on the magnetic impurity strength, the suppression of T_c by spin-flip scattering can be faster or slower than in the standard mean-field theory. Our results are presented in arXiv:1703.02126.

Charge transport in Josephson junction arrays: disorder, decoherence and dissipation

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Josephson junction arrays should be the ideal system in which to study one-dimensional charge transport. They are relatively easy to fabricate, their properties can be tailored at will and the orthodox theory of tunnelling through Josephson junctions is very well understood. However, the transport characteristics of a Josephson junction array vary drastically as a function of parameter space and so a quantitative model for their current response across all regimes has proven elusive. In this presentation I will discuss the fundamentally important roles that disorder, decoherence and dissipation play in transport through these circuits and why the traditional models are just not sufficient. In doing so I will provide some examples where we are now finally able to obtain quantitative agreement between theory and experiment. I will then discuss the open questions and future prospects for a unified theory for charge transport in arrays of Josephson junctions.

Towards single shot readout in double-sided coaxial circuit QED

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A 3-dimensional coaxial architecture for circuit quantum electrodynamics has been recently proposed and the experimental operation of a single-cell has been successfully demonstrated[1]. The basic unit of this architecture is made of a superconducting qubit and a linear resonator which are placed on the two opposite sides of a single chip. The main advantage of this double-sided coaxial geometry is to allow out-of-plane readout of the device, providing easy scalability to large arrays of qubits. Here we present the possibility to operate a single cell of such coaxial architecture in the single shot measurement regime. This is possible via the adoption of a Josephson parametric amplifier (JPA). We developed and characterised a lumped element JPA, based on well-established design[2], in order to exploit it for single shot readout in double-sided coaxial circuit QED.

[1]J. Rahamim et al. Appl. Phys. Lett. 110, 222602 (2017)
[2]X. Zhou et al. Phys. Rev. B, 89:214517, (2014).

Vortex Escape from Columnar Defect in a Current-Driven Superconductor

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Extended linear defects with a diameter of a few nanometers in high-temperature superconductors (HTS) are known as strong pinning sites for Abrikosov vortices, preventing them from motion and related energy dissipation. We report on theoretical and numerical study of a single vortex depinning and its subsequent dynamics in HTS film with extended c-oriented linear defects under the effect of the Lorentz force, transport current and external magnetic field. Numerical simulation of the stability threshold for the pinned vortex state and its subsequent escape from linear defect has been performed. The stability threshold for the onset of vortex escape from the defect, the averaged critical current density and its dependence on the HTS film thickness are found. The relation for the angular dependence of the critical current on the inclination angle of the applied magnetic field is obtained. The results are in good agreement with experimental data available. The non-stationary regime of the vortex escape is investigated and the time-dependent solution for the vortex displacement from the defect is obtained. It evidently demonstrates delay effects in vortex escape process and corresponding resistive response of a superconductor. The work is supported by the RFBR (projects No. 15-07-06082-a, 17-01-00973-a).

Light-sound interconversion in optomechanical Dirac materials

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Analyzing the scattering and conversion process between photons and phonons coupled via radiation pressure in a circular quantum dot on a honeycomb array of optomechanical cells, we demonstrate the emergence of optomechanical Dirac physics. Specifically we prove the formation of polaritonic quasi-bound states inside the dot, and angle-dependent Klein tunneling of light and emission of sound, depending on the energy of the incident photon, the photon-phonon interaction strength, and the radius of the dot. We furthermore demonstrate that forward scattering of light or sound can almost switched off by an optically tuned Fano resonance; thereby the system may act as an optomechanical translator in a future photon-phonon based circuitry.

Current blockade in superconducting nanowires: coherent quantum phase slip or Coulomb blockade?

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The inclusion in quantum circuits of elements exploiting the phenomenon of coherent quantum phase slip (CQPS), with potential applications in areas including quantum metrology and quantum sensing, has been a prospect since the conception of the CQPS junction as the precise charge-flux dual of the Josephson junction. CQPS has been shown to be exhibited by nanowires of superconducting materials sufficiently close to a superconductor-insulator transiton, and a characteristic feature of CQPS is a current blockade at low bias. While this is at first sight similar to the familiar Coulomb blockade of small devices, its physical origin is rather different and, in the CQPS device, it should be controlled by the energy scale for CQPS and not by a characteristic charging energy. Distinguishing between the two effects is an important element of the development of CQPS devices and in this presentation I will present the latest results of our investigations in this area.

Measurement-based quantum computation with mechanical cluster states

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We consider opto- and electro-mechanical quantum systems composed of a driven cavity mode interacting with a set of mechanical resonators. We show that this set-up is rich enough to allow for (i) the generation of universal continuous-variable cluster states, (ii) their tomographic reconstruction, and (iii) general Gaussian quantum computation. In particular, we propose a scheme for generating continuous-variable graph states of arbitrary size and shape. The main feature of this scheme is that the graph states are hosted in the mechanical degrees of freedom, which are dissipatively driven to the desired target state via a multi-tone drive of the cavity mode. Then, we show that, designing a suitable interaction profile between the cavity mode and the mechanical resonators, the statistics of an arbitrary mechanical quadrature can be encoded in the cavity field, which can then be measured. This in turn allows for the full tomographic reconstruction of the resonators state. Finally, exploiting again measurements of the cavity field only, we provide a method to realize the measurements over the mechanical cluster state needed to perform arbitrary Gaussian operations – a necessary part of the toolbox of measurement-based quantum computation.

Single-electron tunneling as a tool for quantum environment engineering

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Superconducting quantum circuits hold great potential in providing revolutionizing practical applications such as quantum sensing or computing. For these applications, it is important to initialize the quantum devices very close to a pure state. Once initialized, the time evolution of the respective quantum states depends strongly on the effective temperature of the quantum degrees of freedom, which can be controlled by their coupling to the environment. Here, we present a method for fast initialization and for an in-situ control of the coupling strength between quantum circuits and the environmental bath. We realize direct cooling of a superconducting resonator mode using voltage-controllable quantum tunneling of electrons in a nanoscale refrigerator. In addition to cooling, we use the tunnel junctions to tune the resonator coupling strength to the environment, i.e., its internal quality factor by orders of magnitude. We extend this concept to superconducting qubits, where the tunable environment can be used for fast qubit reset, to study non-Markovian qubit dynamics, and for dissipation-assisted quantum annealing.

Quantum Oscillations of Resistance and Magnetization in Europium-doped 3D Topological Semimetal Cd_3As_2

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The temperature dependence of the resistance of a 3D topological semimetal Cd_3As_2 doped with a small amount of a europium is completely described by an exponential (semiconducting) term with a gap of about 30 K and a linear phonon term with a negative residual resistance which indicats on the unusual scattering of current carriers. However, against such background, we found a weak contribution to the resistance which oscillats with temperature and magnetic field. An analogous contribution is also manifested in the field dependence of the magnetization. Similar phenomena were previously observed in magnetic semiconductors [1] and were associated with the temperature dependence of the Fermi level and a change in its position relative to the Landau levels arising in the quantization of electron orbits in a magnetic field. In our case, the appearance of such phenomena can be a consequence of the splitting under the influence of magnetic impurities of Dirac nodes in the electronic spectrum into Weyl nodes, the presence of a hidden semiconductor gap that affects the population of levels and the behavior of europium ions due to their non-integral valence.

[1]A.D. Balaev, V.V. Valkov, V.A. Gavrichkov, et al., Uspekhi, Physics, UFN, 167 (9), 1017 (1997)/

About existence of topological phases of magnetic impurities Eu^{2+} in 3D topological Dirac semimetal Cd_3As_2

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The influence of magnetic impurities Yb and Eu on the magnetic properties of α-Cd_3As_2 is studied. It is found that when small doping changes the type of the dependence of the transverse magnetoresistance on the field, and upon doping Eu its sign changes from positive to negative. Data on the magnetic susceptibility and saturation magnetization showed the presence of an additional phase of Eu^{2+} ions magnetized against the external field. Measurements of electron spin resonance (ESR), carried out at high temperatures, allow us to conclude that this phase consists of Eu^{2+} ions located in interstices positions - tetrahedral vacancies in fluorite type cell. Whereas the main phase consists of the Eu^{2+} ions in the positions substituting of the Cd^{2+} ions. The ESR data show anomalous large values of the g - factor of the Eu^{2+} ions, which in its turn indicates very large values of the g factor of the conduction electrons (g about 16-18). Analysis of the role of the RKKY interaction[1] in this situation leads to the conclusion that the RKKY interaction in the classical view can not lead to change of a sign of interaction selectively in dependence on position types in the crystal lattice. Consequently, we are dealing with a new type of indirect interaction[2], whose agents are the local symmetry breakings of the crystal by magnetic ions. This interaction leads to the splitting of twotime degenerate Dirac nodes by anological with splitting of electronic states with different spin directions and formation two topological phases of magnetic impurities.

[1] Jin-Hua Sun, Dong-Hui Xu, Fu-Chun Zhang,Yi Zhou, Phys.Rev. **B 92**, 195124 (2015)
[2] Dimitri Kurdgelaidze, GESJ: Physics, **2(8)**, 10 (2012)

Wafer-level Josephson junction fabrication process enabling sub-micrometer feature size

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At VTT we have an established niobium trilayer Josephson junction fabrication line[1] that has demonstrated its capacity in a multitude of academic and industrial applications including especially sensors and sensor readout, but also several quantum technology demonstrators. However, the conventional process has certain undesirable features such as a limited selection of dielectric materials causing microwave losses and nonlinearity at sub-Kelvin temperatures, and limited minimum junction size of about 2 μm. To mitigate these shortcomings we have developed a new cross-layer junction process which enables sub-micrometer junctions and designs with less restrictions stemming from dielectric properties. At the same time, the process scalability is maintained as it is based on optical lithography and automated cassette-to-cassette process steps on 150 mm silicon substrates. We present the main features of the process, and show room temperature and low temperature characterization results verifying good yield of junctions down to the dimension scale of 200 nm. We also discuss the process-related performance improvements characterized from the first actual components, the Josephson parametric amplifiers and SQUID magnetometers fabricated with the process.

[1]M. Kiviranta et al., IEEE Trans. Appl. Supercond. 26, 2016.

Normal-metal quasiparticle traps for superconducting qubits

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Tunneling of quasiparticles across a Josephson junction is an intrinsic mechanism of decoherence for superconducting qubits. The associated qubit relaxation rate scales linearly with the quasiparticle density, whose experimental value at low temperatures is many orders of magnitude higher than expected. A normal metal that is tunnel-coupled to a superconducting qubit can trap quasiparticles away from the junction, but the effective trapping rate is limited by slow relaxation inside the normal metal. We show that proper trap placement can substantially reduce the relaxation time of excess quasiparticles; at the same time, it can suppress the steady-state density at the junction. Therefore, normal-metal quasiparticle traps have the potential to improve coherence time of qubits. The inverse proximity effect opens up new decay channels and thus can increase the qubit relaxation rate, but these negative side effects decrease exponentially with trap-junction distance.

The Fundamental Bound of Single-Qubit Gate Error

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Prototypes of quantum computers have been developed to a point where the key question is the large-scale integration of quantum bits into a useful processor. To keep the processor at a reasonable size, the qubit operations need to be both precise and energy-efficient. This raises the questions: how is the precision of quantum gates limited by the amount of available energy? And how many high-quality gates is it possible to perform with limited amount of energy? In this work[1], we derive the greatest lower bound for the gate error induced by a single bosonic drive mode of given energy. This type of error, caused by quantum-mechanical uncertainties in the pulse, is inversely proportional to the pulse energy, and hence seems to pose a trade-off in the power management of the quantum computer. These challenges further motivate the investigation of control methods alternative to the present standards, such as generating or redistributing control pulses at the chip level. Thus we propose a control protocol where multiple gates are generated with a single control pulse, and back-action-induced correlations between the pulse and computational qubits are removed using auxiliary qubits.

[1]J. Ikonen, J. Salmilehto, and M. Möttönen, npj Quantum Information 3, 17 (2017).

Graphene Josephson junctions integrated in superconducting microwave cavities

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We report on the fabrication and characterization of hBN-encapsulated graphene Josephson junctions (gJJ) embedded in superconducting coplanar waveguide resonators. The devices consist of a hBN-Gr-hBN stack which is edge-contacted to a MoRe resonator. The cavity is designed to be galvanically accessible allowing for simultaneous DC and RF characterization of the gJJ. Also a local gate voltage is used to tune the gJJ doping and critical current. This architecture could allow for the implementation of gate tunable Josephson electronics, such as qubits or parametric amplifiers, based on gJJ. Moreover, these devices could provide insight into the relation of DC and RF characteristics of SNS proximity junctions.

Carrier-induced Magnetic Solitons and Metal-insulator Transition in Diluted Magnetic Semiconductors

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Diluted magnetic semiconductors (DMS) have attracted much attention because of the combination of magnetic and semiconducting properties [1]. The ferromagnetism in DMS has been investigated theoretically within the mean field approximation by a model Hamiltonian or by ab initio methods. So far, no consensus has been reached about the origin of the ferromagnetism. Detailed measurement of transport very close to metal-insulator transition (MIT) in diluted magnetic semiconductors (Ga,Mn)As has been reported [2]. In addition, interesting phenomena such as the photo-induced magnetic soliton in DMS have been discovered [3]. Thus, it has been required to consider the behaviour of solitons such as the hedge-hog-like soliton and the domain wall from the viewpoint of quantum theory. One(IK) of the present authors has discussed the localization mechanism, using the gauge-invariant Lagrangian density for the hole-induced magnetic solitons [4,5]. In this study, we will discuss localization mechanism of DMS and compare with experimental results [2], by using effective Lagrangian of diffusion modes. [1] H. Ohno, Science 281,951(1998) [2] S. Katsumoto et al.,Mater.Sci.Eng.84,88(2001) [3] S. Koshihara et al., Phys. Rev. Lett. 78,4617(1997) [4] I. Kanazawa, Phys. Lett. A355, 460(2006) [5] I. Kanazawa, Physica E 40,277(2007)

How to test the dynamical locality with superconducting circuits

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A moving charge under an external electromagnetic field acquires an intriguing quantum phase shift, known as the Aharonov-Bohm phase, even without a local overlap of the charge and the field. This is usually described in terms of the electromagnetic potentials, implying that local and causal interactions are not specified for the effect. This type of nonlocality is dynamical in that it is a nonlocality of the quantum equation of motion, and is considered to be inherent in quantum theory. In contrast to this common notion, we can construct a local framework based on the Lorentz-covariant field interactions (LCFI) without relying on the potentials. This framework provides correct predictions for the AB effect.[1] The key point is whether one can find a way to test the dynamical (non)locality in a real experiment. Here we propose two experimental setups with superconducting circuits for unambiguous tests of this type of locality: (i) Andreev interferometer without a loop under an external magnetic field, and (ii) a Cooper pair box under an electric field at a distance. In both cases, external-field-dependent phase shifts are predicted in the LCFI approach, whereas the standard potential-based theory fail proper description of these phases. These results have profound implications as it can settle the dynamical locality in the quantum electromagnetic interactions.

[1]See K. Kang, Phys. Rev. A **91**, 052116 (2015).

Ab Initio Calculation of Superconductivity and Electron-Phonon Interaction in The Body Centered Tetragonal $CaPd_2Ge_2$

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Ab initio pseudopotential calculations have been performed to study the structural, electronic and vibrational properties of $CaPd_2Ge_2$ crystallizing in a body-centered tetragonal $ThCr_2Si_2$-type structure. The calculated second-order elastic constants indicate that $CaPd_2Ge_2$ is mechanically stable and behaves in a ductile manner. Our electronic results show that the density of states at the Fermi level is mainly dominated by Pd d and Ge p orbitals. The linear response method and the Migdal-Eliashberg approach have been used to calculate the Eliashberg spectral function for $CaPd_2Ge_2$. By integrating the Eliashberg spectral function, the average electron-phonon coupling parameter (λ) is found to be 0.66 for $CaPd_2Ge_2$. Using the calculated electron-phonon coupling parameter values, the superconducting critical temperatures for $CaPd_2Ge_2$ are found to be 1.69 K, which is in excellent agreement with its experimental value.

Coupling superconducting qubits to high overtone bulk acoustic phonons

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Superconducting qubits are the leading platform for realizing quantum computation. They are flexible in design, and exhibit relatively long coherence times. Nonetheless, it will be beneficial to extend their properties using hybrid systems involving disparate degrees of freedom coupled to the qubits. Atomic systems have been investigated to this end as long-lasting quantum memories, and various other systems for interfacing the qubits to external world. Mechanical oscillators can be a promising means to realize a hybrid system offering such benefits, but in previous investigations, either high mechanical coherence has not been reached, or active cooling is needed in order to keep a low-frequency mechanical system in the quantum limit. Here we realize the interfacing of a superconducting transmon qubit with 6 GHz mechanical modes in a piezoelectric thin film. Specifically, the mechanical oscillations are high overtones that dilute most of the energy in the low-loss substrate. We reach the strong coupling with coupling energies of 6 MHz, while the mechanical modes are deep in the ground state in a dilution refrigerator. In time domain measurements, we drive Rabi oscillations between the ground state and detuned oscillator-type state, thereby adiabatically preparing approximate single-phonon Fock states.

Quantum Gates for Propagating Microwave Photons

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We report a generic scheme to implement transmission-type quantum gates for propagating microwave photons, based on a sequence of lumped-element components on transmission lines [1]. By choosing three equidistant superconducting quantum interference devices (SQUIDs) as the components on a single transmission line, we experimentally implement a magnetic-flux-tunable phase shifter and demonstrate that it produces a broad range of phase shifts and full transmission within the experimental uncertainty. Together with previously demonstrated beam splitters, these phase shifters can be utilized to implement arbitrary single-qubit gates. Furthermore, we theoretically show that replacing the SQUIDs by superconducting qubits, the phase shifter can be made strongly nonlinear, thus introducing deterministic photon–photon interactions. These results critically complement the previous demonstrations of on-demand single-photon sources and detectors, and hence pave the way for an all-microwave quantum computer based on propagating photons.

[1]arXiv preprint, arXiv:1703.02241 (2017)

Stability of the superconducting d-wave pairing towards the intersite Coulomb repulsion in CuO_2 plane

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Within the spin-fermion model for cuprate superconductors, the influence of the intersite Coulomb interactions between holes located at the nearest and next-nearest neighbor oxygen ions of CuO_2 plane on the implementation of the $d_{x^2-y^2}$-wave pairing is studied. It is shown that because of the two-orbital character of the subsystem of holes located at oxygen sites and the spatial separation of this subsystem from that of spins at copper ions, the superconducting phase in high-T_c superconductors is stable towards the strong Coulomb repulsion V_1 of holes located at the nearest-neighbor oxygen sites if the order parameter has the $d_{x^2-y^2}$-symmetry. This effect is due to the symmetry properties of the Fourier-transform of the intersite Coulomb interaction. It is shown that an account for the intersite interaction between holes located at the next-nearest-neighbor V_2 leads to the suppression of the d-wave pairing, however superconductivity disappears completely only at unphysically large values of V_2.
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Charge soliton enhanced environment impedance in one dimensional array of Josephson junctions

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We conduct microwave impedance measurements on a one-dimensional (1D) arrays of Josephson junctions to experimentally determine the Josephson inductance and shunt resistance of the constituent junction. The effective Josephson energy provides an estimation of the environmental impedance, which is greatly increased due to phase fluctuations in three neighboring junctions. This enhancement is attributed to the charge solitons in the 1D system. In general, the environmental impedance is dominated by the junction's normal resistance in the superconducting phase coherent regime, but overwhelmed by zero-bias resistance and differential resistance, respectively, in the Coulomb blockaded regime and in the phase fluctuating regime.

Coulomb Blockade in a Superconducting Single Electron Transistor: Transition from Weak to Strong Coupling

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A small island connected by two tunnel junctions and a gate electrode forms a single electron transistor (SET) that shows Coulomb blockade (CB) effects. In the case of weak-coupling, Orthodox Theory (OT) can be used to quantitatively describe the behavior of these devices even when considering superconducting transport [1,2]. Transport in the strong-coupling regime, however, is not yet fully understood and difficult to address with traditional SETs.
By using all-superconducting SETs, which are composed of an AlO_x tunnel barrier and a mechanically controlled break junction (MCBJ), we are able to continuously tune the transport from weak to strong coupling within one sample. In the weak-coupling regime our observations are in good agreement with OT [1] and allow a full characterization of the samples. When gradually enhancing the coupling, we observe several novel transport phenomena caused by multiple Andreev reflection as well as unexpexted features like a renomalization of the charging energy in the strong coupling case.
[1] R. J. Fitzgerald, Phys. Rev. B 57, R11073(R) (1997) [2] K. K. Likharev, Proc. IEEE 87, 606 (1999)

Bell Inequality Test Using Optomechanics

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We propose a homodyne detection scheme aimed at testing the CHSH Bell inequality. In our setup, an optomechanical device constituted by two cavities coupled to a common mechanical resonator is used to generate the Einstein-Podolsky-Rosen correlations between two output signals whose quadrature amplitudes are measured by spatially separated homodyne detectors. We address several of the possible loopholes that can arise in this scheme and discuss microwave and optical realizations of the setup. Furthermore, we consider the possibility of using the system for quantum key distribution using the quadrature amplitudes.

Nonlinear Quantum Langevin Equations for Mesoscopic Systems

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The description of an open quantum system in terms of Input-Output equations usually leads to the formulation of the system dynamics in terms of Quantum Langevin Equations (QLEs) exhibiting dissipation and noise properties which are linear in the system and noise operators, respectively. We show here that, in the presence of an appropriate coupling between system and environment it is possible to obtain a description in terms of nonlinear QLEs. Furthermore, we show that, in the context of mesoscopic systems, in particular in circuit QED setups, the presence of impurities modeled as two-level systems naturally results in a description in terms of nonlinear QLEs.

Circuit-QED with Left-handed Superlattice Metamaterials

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Recently, a quantum mechanical phase transition of a qubit's tunneling probability was predicted in a transmission line coupled to a left-handed circuit[1]. In this work, we investigate a superlattice of two alternating left-handed circuit cells instead of a normal left-handed circuit. This gives rise to a new energy band in which the mode density can reach extremely high values, and with that, strong multimode coupling of the qubit is possible. Furthermore, we use adiabatic renormalization to find the effective tunneling element of the qubit and, in contrast to the recent work, we find two additional phases of partial localization.

[1]Phys. Rev. Lett. 111, 163601 (2013)

Spin–(un)Polarized Tunneling into Helical Edge States in Fermionic Approach: Conductances and Asymmetry

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We consider tunneling into the Luttinger liquid edge states of quantum spin Hall system from the tip with either unpolarized or polarized electrons. We use the fermionic representation and the scattering state formalism, in order to compute the renormalization group (RG) equations for the linear response conductances. We analyze tunneling from the tip of the spinful wire to the edge state. In this case we demonstrate the existence of both fixed lines and conventional fixed points of RG equations, and certain proportionality relations holding for conductances during renormalization.[1] Further, we consider tunneling from the spin-polarized tip. In the lowest order of the tunneling amplitude we confirm previous results for the scaling dependence of conductances. Going beyond the lowest order we show that the interaction affects not only the total tunneling rate, but also the asymmetry of the injected current.[2] The helical edge state forbids the backscattering, which leads to the possibility of two stable fixed points in the RG sense, in contrast to the Y-junction between the usual quantum wires. The scaling exponents and phase portraits are obtained in all cases.

[1]D. N. Aristov, R. A. Niyazov, Phys. Rev. B, 2016
[2]D. N. Aristov, R. A. Niyazov, Europhysics Letters, 2017

Quantum Backaction Evading Measurement of Collective Mechanical Modes

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The standard quantum limit constrains the precision of an oscillator position measurement. It arises from a balance between the imprecision and the quantum backaction of the measurement. However, a measurement of only a single quadrature of the oscillator can evade the backaction and be made with arbitrary precision. We demonstrate quantum backaction evading measurements of a collective quadrature of two mechanical oscillators, both coupled to a common microwave cavity. This allows for quantum state tomography of two mechanical oscillators, and provides a foundation for macroscopic mechanical entanglement and force sensing beyond conventional quantum limits.

New perspective on the 2D metal-Insulator Transition

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The discovery of low-dimensional metallic systems such as high-mobility metal oxide field-effect transistors, the cuprate superconductors, and graphene, silicene, phosphorene, conducting oxide interfaces (e.g., $LaAlO_3/SrTiO_3$), and a large variety of transition metal chalcogenide and dichalcogenide systems contradicts the seminal theory for transport in disordered metals that predicts that the metallic state cannot exist in two dimensions (2D) [1]. A key issue in such studies is the nature of the metal insulator transition (MIT) in 2D. Since the MIT is a quantum phase transition (one that occurs at $T = 0$ K) the transport properties should be independent of the chemical and structural details of the system. In this presentation, we will demonstrate that a generic phase diagram for the 2D MIT can be constructed for two very different systems: 1) highly disordered RuO_2 nanoskins and 2) plasma-functionalized graphene. This phase diagram consists of three regions: metallic, weakly localized insulator with conductivity, $\sigma \sim \log(T)$, and strongly localized insulator. We will present details of the transport properties of the disordered RuO_2 nanoskins and plasma-functionalized graphene near their respective MITs.

[1]Abrahams, E., Anderson, P.W., Licciardello, D.C., & Ramakrishnan, T.V. "Scaling theory of localization: Absence of quantum diffusion in two dimensions". *Phys. Rev. Lett.* **42**, 673-676 (1979).

Robust accelerated adiabatic control by synthetic gauges in a three-level system

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Quantum control by adiabatic pulses presents the advantage of robustness under errors in timing, yet it is inherently slow. Here we present an implementation of the superadiabatic (transitionless) protocol in a three-level system realized with a transmon superconducting circuit. Using a two-photon transition, we show that the transfer of population from the ground state to the second excited state by stimulated adiabatic Raman passage can be shortened to only a few tens of ns, approaching the quantum speed limit. We show that this type of driving has features resembling the Aharonov-Bohm effect, where the phases of the microwave pulses play the role of a gauge field.

Flux-Tunable Dissipation for Superconducting Quantum Circuits

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Circuit quantum electrodynamics (cQED) is one of the most promising approaches for building a large-scale quantum computer. However, further development steps are needed to obtain this goal. Especially, fast initialization of qubits is beneficial for various error correction codes. In the framework of cQED, we experimentally investigate a tunable environment for a qubit utilizing a normal-metal resistor. Here, we demonstrate tuning of the loaded quality factor of the system from above 10^5 down to a few thousand. Essentially, our system consists of two coupled resonators: one with a high quality factor, and the other with a low quality factor and a tunable resonance frequency achieved with a superconducting quantum interference device. An on-chip resistor determines the low quality factor. The system can potentially be used for fast qubit initialization.

Driven Quantum-to-Classical Transition of a Dispersive Transmon Qubit

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We study a system consisting of a driven co-planar waveguide resonator coupled to a superconducting transmon. At small driving power the transmon behaves as a quantum two-level system and the cavity-transmon system can be described with the Jaynes-Cummings model. As the drive power is increased, higher excited states of the transmon are occupied and the two-level approximation becomes inaccurate. Eventually the system has so many exitations that it can be thought of as classical. We use the Floquet method to calculate the dressed energy levels of the driven system and obtain the absorption spectrum of the system with Fermi's golden rule. We show that by increasing the drive power one can switch continuously between purely quantum mechanical and essentially classical behavior. We demonstrate this quantum-to-classical transition experimentally[1] and show that the measured data agrees well with our theory.

[1]I. Pietikäinen, S. Danilin, K. S. Kumar, D. S. Golubev, J. Tuorila, and G. S. Paraoanu, arXiv:1610.09153 (2016)

Enhancing Quantum Optomechanics by Squeezed Light

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We propose two optomechanical interfaces, to upload a nonclassical state to a mechanical oscillator, and to realize quantum nondemolition (QND) interaction between (and to entangle) two mechanical oscillators embodied in distant optomechanical cavities. Both interfaces are based on pulsed QND optomechanical coupling and techniques available in quantum optics.
We prove that the performance of the interfaces can be enhanced by quadrature squeezing of light. Our analysis shows that both interfaces are feasible with current technology and can be used to merge the fields of optomechanics and experimental quantum optics.

Non-invasive refrigeration with superconducting single-electron junctions

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I present the model of a superconducting tunnel junction which refrigerates a nearby metallic island without any particle exchange. Heat extraction is mediated by charge fluctuations in the coupling capacitance of the two systems. The interplay of Coulomb interaction and the superconducting gap reduces the power consumption of the refrigerator. The island is predicted to be cooled down to temperatures close to 50 mK, for realistic parameters. This mechanism can be applied to create local temperature gradients in tunnel junction arrays.

Millimeter-Sized Piezoelectric Resonators Near the Quantum Ground State

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The observation of quantum effects in macroscopic mechanical systems has received a lot of attention during the last years. First because it can aid our understanding of the fundamentals of quantum theory. Second, this type of measurement needs extremely sensitive and low noise setups, enabling applications in other areas. Finally, the macroscopic degrees of freedom show promise for quantum computation applications. We propose and demonstrate a new cavity optomechanical scheme which involves a mm-sized piezoelectric quartz mechanical oscillator, five orders of magnitude more massive than in earlier optomechanical experiments [Nat. Commun. 6, 8491 (2015)], relatively near the ground state. Its motion is coupled to a charge qubit which translates the piezo-induced charge into an effective radiation-pressure interaction between the disk and a microwave cavity. We present techniques to manipulate the mechanical mode shape and increase the qubit-piezo coupling. In experiment, we measure the thermal motion of the lowest mechanical shear mode at 7 MHz down to 30 mK, corresponding to roughly 10^2 quanta in a 20 mg oscillator. Furthermore, we observe back-action cooling of the motion by the qubit, demonstrating control of macroscopic motion by a single Cooper pair. We also predict that tuning the piezoelectric crystal and qubit design will allow cooling and measurement of the mechanical resonator at the ground state, opening opportunities for macroscopic quantum experiments.

QPS Induced Shot Noise in Josephson Junctions and Superconducting Nanowires

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At low temperatures non-equilibrium voltage fluctuations can be generated in current-biased superconducting nanowires due to proliferation of quantum phase slips (QPS) or, equivalently, due to quantum tunneling of magnetic flux quanta across the wire. This phenomenon is similar to macroscopic quantum tunneling of the phase in Josephson junctions and weak links.
In this talk we review recent theoretical results on the issue and present our recent calculations of the voltage noise generated by quantum phase slips in short superconducting bridges and Josephson junctions. In contrast to our previous studies of long superconducting wires, here we account for an external environment which is the main source of dissipation in this case. As a result, some of our predictions differ substantially from those formulated before in the long wire limit. We discuss similarities and differences between various limiting cases demonstrating that in both superconducting nanowires and Josephson junctions quantum phase slips generate quantum shot noise which vanishes at frequencies beyond some threshold value in the zero temperature limit.
The results of our theoretical analysis can be directly tested in future experiments with superconducting nanowires and Josephson junctions.

Current contributions in a superconducting SET due to Multiple Andreev Reflections

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A small island connected to two leads via two tunnel junctions and a capacitively coupled gate electrode forms a single electron transistor (SET). The transport through such a SET is highly non-linear and shows Coulomb blockade (CB) effects [1]. Measuring in superconducting state (SSET), the single-electron transpport processes are shifted towards higher voltages by the superconducting gap. Additinoal contributions due to Cooper pairs and Andreev reflections occur at voltages above the CB range but inside the superconducting gap. In the weak coupling regime all phenomena can be described by Orthodox Theory (OT) [2].
We investigate a SSET formed by one aluminum oxide tunnel barrier and one mechanically controllable break junction (MCBJ). We will concentrate here on phenomena that are observed when the MCBJ is broken to form a mere tunnel contact. By applying a magnetic field the samples are fully characterized in the normal conducting state. We present measurements on samples differing in the transparency of the oxide barrier, either allowing only tunneling and Josephson transport or in addition Andreev transport, where additional contributions to the current due to multiple Andreev reflection can be observed, giving first indications of coherent transport. The measurements are compared with the predictions of (OT).
[1] K. K. Likharev, Proc. IEEE 87, 606 (1999) [2] R. J. Fitzgerald, Phys. Rev. B 57, R11073(R) (1997)

Coherence and control in double sided coaxial circuit QED

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Superconducting circuits are well established as a strong candidate platform for the development of quantum computing. In order to advance to a practically useful level, architectures are needed which combine arrays of many qubits with selective qubit control and readout, without compromising on coherence. We have developed a coaxial circuit QED architecture in which qubit and resonator are fabricated on opposing sides of a single chip, and control and readout wiring are provided by coaxial wiring running perpendicular to the chip plane making the architecture potentially scalable to arrays of many qubits. Here we present T_1 and T_2 measurements for single qubits in our architecture as well as a single qubit gate fidelity found by randomized benchmarking. We discuss radiative and dielectric loss channels and argue that dielectric loss is dominant. Finally, preliminary measurements of addressability on a multi-qubit device are presented.

Tying quantum knots

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The theory of knots has a long history in mathematics and physics since Lord Kelvin proposed knots in ether as a model of atoms. Although this proposal did not work in physical reality, it gave a birth to mathematical study of knots. Recent experiments have observed knots in a variety of classical contexts, including nematic liquid crystals, DNA, optical beams, and water. However, no experimental observations of knots have yet been reported in quantum matter. We demonstrate the controlled creation and detection of knot solitons in the order parameter of a spinor Bose–Einstein condensate. The observed texture corresponds to a topologically nontrivial element of the third homotopy group and exhibits the celebrated Hopf fibration, which unites many seemingly unrelated physical phenomena. The very good agreement between the experiments and theory provides conclusive evidence for the existence of the knot soliton. Our observations establish an experimental foundation for future studies of knot stability and dynamics within quantum systems.

Efficient Protocol for Qubit Initialization with a Tunable Environment

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We propose[1] a rapid qubit initialization protocol that uses an engineered dissipative environment and does not essentially increase the qubit dissipation during computations. The protocol can be realized for a superconducting qubit by coupling it to a thermal bath through two LC resonators. One of the resonators is directly coupled to the cold bath and its resonance frequency can be dynamically adjusted. On-demand ground-state initialization is achieved by visiting in succession the resonances with the other resonator and the qubit, where the respective relaxation rates are increased by several orders of magnitude. As a consequence, possible excitations in the resonant constituents decay fast to the desired fidelity. In the end, the adjustable resonator is rapidly detuned, which effectively decouples the qubit from the engineered environment. We solve the Markovian master equation for our protocol and show that with optimized and realistic superconducting circuit parameters the initialization time is roughly 300 ns, which is almost an order-of-magnitude improvement to the current experimental benchmark. Importantly, an intrinsic qubit temperature of 100 mK can be reduced to one third, corresponding to a qubit excited-state occupation of 10^{-6} at the end of the protocol. Finally, we discuss the possibility of studying strong environmental coupling with the stochastic Liouville–von Neumann equation.

[1]J. Tuorila, M. Partanen, T. Ala-Nissila, and M. Möttönen, arXiv:1612.04160 (2016).

Keldysh Green's function technique: Accessing the transient dynamics in laser-driven superconductors

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A standard approach to nonequilibrium many-body problems is the Keldysh Green's function technique.[1] Dynamical information about the studied system, e.g. electric currents, photoemission spectroscopy etc., is encoded into the Green's function. To access this, we have to consider coupled integro-differential equations (Kadanoff–Baym equations), whose efficient solution is far from trivial.[2] The Generalized Kadanoff–Baym Ansatz (GKBA) offers a simplification by decomposing the two-time-propagation of the Green's function into the time-propagation of a time-local density matrix.[3] In this contribution, we discuss the single-time-propagation of the Green's function à la GKBA, and we present some benchmark simulations against the full solution of the Kadanoff–Baym equations. Further discussion is devoted to applications, e.g., laser-driven superconductors[4] and excitonic insulators[5], where we investigate the dynamics of competing orders and how the balance between them could be controlled by laser driving.

[1]G. Stefanucci and R. van Leeuwen, *Nonequilibrium many-body theory of quantum systems*, CUP (2013)
[2]A. Stan, N. E. Dahlen, and R. van Leeuwen, J. Chem. Phys. **130**, 224101 (2009)
[3]P. Lipavský, V. Špička, and B. Velický, Phys. Rev. B **34**, 6933 (1986)
[4]M. A. Sentef, A. Tokuno, A. Georges, and C. Kollath, Phys. Rev. Lett. **118**, 087002 (2017)
[5]Denis Golež, Philipp Werner, and Martin Eckstein, Phys. Rev. B **94**, 035121 (2016)

Pulsed Quantum Non-demolition Interaction in Opto- and Electromechanics

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Quantum optomechanics has been rapidly developing during last years. One of the promising research directions is the pulsed opto- and electromechanics in which the radiation modes are defined in temporal pulses allowing to avoid a number of restrictions imposed by the continuous regime. Quantum non-demolition interaction between the radiation and the mechanical system is of particular interest. It is the most general type of interaction which may be used for construction of any other interactions between multiple oscillators. At first we explore the pulsed continuous variable opto- and electromechanical transducer which entangles two directly non-interacting radiation modes via a set of sequential interactions with the noisy mechanical mediator. We show that with the help of the geometric phase effect it is possible to eliminate the influence of the mediator and obtain high performance of the proposed protocol for opto- and electromechanical setups even for large thermal occupation of the mechanical system. We also prove the feasibility of this setup for the stroboscopic regime in which the cavity bandwidth is much larger than the mechanical frequency, and we demonstrate efficiency of this scheme. We go further with the stroboscopic regime and explore the setup allowing to entangle two vibrational modes of the same mechanical oscillator (e.g. different modes of the microtoroid resonator). We find the ways to produce maximum of the generated entanglement with the help of squeezing on the optical side and we prove the feasibility of such device for the state-of-the-art optomechanical experiment.

Dissipation Induces a Power-law Decay of s-wave Superconducting Gap above the Transition Temperature

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Recently, controlling the dissipation between system and environment has attracted much attention for stabilizing a desired quantum coherent state in the system. The superconducting state is the one of the most typical coherent states of electrons, which has versatile application, e.g. qubits, but appears usually near the zero temperature. The quantum coherence disappears at a finite temperature because of the thermal excitation of quasiparticles. To make the superconductivity more stable at higher temperatures by dissipation is, therefore, important in terms of the fundamental physics as well as its application. Here, we theoretically introduce an artificial dissipation that leads to a loss of harmful quasiparticles in the conventional s-wave superconductor in the thermal bath, and show that the dissipation is helpful for enhancing the stability of superconductivity even above the original transition temperature; From the analysis of the quantum master equation, it is found that when we increase the bath temperature, the power-law decay of the superconducting gap appears above the transition temperature in the presence of the dissipation. The exponent of the decay is determined by the inverse of the dimensionless strength of the dissipation normalized by the coupling strength between system and bath. We also show that the artificial dissipation is possibly introduced via nonequilibrium electron transport in a superconductor-semiconductor junction.

Observation of dissipative Thouless pumping in a classical harmonic-oscillator chain

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The model proposed by Thouless that described topological quantum transport of electron is one of theoretical cornerstones that brings in topology to modern physics. However, the extension of Thouless transport to general classical physical system is still missing experimentally, on the other hand, numerous topological phenomena has been studied and observed in classical physical system recently. Here, we reports the experimental realization of classical Thouless chain that recently been theoretically proposed using a parametrical controlled harmonic oscillator chain made by conventional complementary metal-silicon processing. We observed discrete character of mechanical vibration transport which can be well described using Thouless topological pump model, and the corresponding topological order are directly measured which is robust even in present of significant dissipation. The results shows that topological physics process as well as programmable topological functional device can be realized in Micro/Nano-electromechanical systems.